Algorithms & Power Systems Architecture:

Using Historical Analysis to Envision a Sustainable Future

Oral History Project

Interviewee: David Hill

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***Abstract*:**

Dr. David Hill is Professor of Electrical Power and Energy Systems at Monash University. He begins by describing his educational background, his early work on systems control and stability theory, and his participation on the Systems Engineering for Power project at Berkeley. He describes working on problems in system stability as formative and underscores his belief that power systems merit consideration as a field of study. He describes working in Sweden following the major 1983 voltage collapse, detailing the importance of finding the right model to analyze what happened and how to prevent it from happening again. He discusses working with Art Bergen and others on modeling advances that are valuable today for addressing power systems with renewables and batteries. He notes the importance of making the theoretical useful in the practical world. He discusses the 1983 voltage collapse in Sweden further, and a model that they were able to verify directly on the power system. He compares the nature of power systems in Sweden, Australia, and other countries. He describes the efforts made to manage risk of an outage during the test. He discusses the relationships between

academia, industry, and others in Sweden, and then in other parts of the world. He underscores the collegial interactions between sectors that allowed for the test, and for people to embrace new approaches. He discusses restructuring of the power industry in Australia, the emphasis on economic efficiency, and the development of markets to manage frequency. He considers the value of historical vertically integrated systems for matters such as area generation control, and the future architecture of power systems, including distribution system operators. He explains that currently vendors of equipment to connect renewables, for example wind turbines, to power systems keep their control settings secret, which creates problems for analyzing outages. He suggests looking for new paradigms for system planning, especially as weather patterns are changing. He offers definitions for resilience, reliability, and stability. He speculates on the future role of ChatGPT, and artificial intelligence generally, in system optimization work. He reflects on his 2022 Bode Lecture. He closes by encouraging young engineers to be optimistic and to always look for the new tool that will help to solve a problem.

<u>Note regarding Transcript and Timestamps:</u>

Timestamps appear in the transcript but may not align with the recording. Pauses and interruptions may have been removed and the overall length of the recording may be reduced.

Transcript:

Julie Cohn (00:00:02):

This is Julie Cohn. I'm conducting an interview with David Hill on January 22nd, 2024, Central Standard Time in the United States, online. Mark Goldberg, Sairaj Dhople, Daniel Molzahn, and Rachel Harris are also participating in this interview and may also ask questions. Dr. Hill, during today's interview, we are especially interested in your early work on control theory as it relates to power systems, but we'd also like to hear your reflections on different approaches to research teams, theoretical constructs, operating experiences in the different parts of the world in which you've worked and collaborated, from Australia to Russia to the United States. We'll begin with some introductory questions and general background information about you. So, if you would, please describe your educational background and your professional positions in the field of electrical engineering and power systems control.

David Hill (00:01:11):

Well, thank you. Thank you, Julie, with pleasure to be here today. My background is going right back, is undergraduate degrees, honors degrees in engineering, and then mathematics. And I've always been interested in systems. From a very early stage, even in my undergraduate days, I got quite fascinated by the whole idea of systems, economic systems, engineering systems, even human systems. So that has underpinned, I think, a lot of the choices I've made over the years. I did a PhD in the University of Newcastle, Australia, where they had a very strong systems and control group led by professors Brian Anderson and Graham Goodwin, who ultimately became—Brian ultimately became president of IFAC, the international control organization. So, it was a very strong systems and control culture there. I did a PhD of a theoretical nature on stability theory, and then was led to the University of California, Berkeley, where also—it was a time when systems in control was the hot topic in electrical engineering.

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It was helping put people on the moon. There were defense implications, which I wasn't so interested in, but it was a very strong area at the University of California, Berkeley. And I was very fortunate at the time that I went there, that they had just achieved a role in a major project called Systems Engineering for Power, led by Lester Fink at the Department of Energy. And this was motivated by the, I believe, the energy crisis in the '70s, late '70s, where there was, concern came from that about the overall efficiency of the system, the whole system. So, this was a fantastic opportunity for me, trained in systems and control. And here was a major project across universities across the whole of the US. I got a postdoc in that program, and they handed me some, being a theoretician, they handed me problems in system stability.

(00:03:38):

So, this was probably the most formative period of my career, because it enabled me to use my background, but got me involved in systems— energy, power and energy problems. But from a systems point of view, and also from a fundamental point of view, which is something that's also carried with me my whole career. And that is, I don't see the power system as just a sandpit for other areas to play in. I believe it's a subject in its own right, with fundamentals, theory, and practice. And just like the communications area or robotics or other areas, we should appreciate everything from theorems to software. And that's been a style that I have stuck to then for my career. Now, after that, I went back to Newcastle, became a professor, then I moved to the University of Sydney, where I set up my own—

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In Newcastle I was still under the wings of the senior control guys, but then my home base became the University of Sydney, where I established a Center for Future Energy Networks, but with side trips to Sweden and Hong Kong, and then back to Sydney. And now I'm kind of semi-retired, but Monash is rebuilding its—in Australia we have a very major energy transition going on, and ours is a special transition because we're an island—a large island. So, we can't depend on other countries to help us out if the sun doesn't shine and the wind doesn't blow. So, this major energy transition needs some of the old timers like me. And so, I've got a couple of years at Monash to help out building a group there and advising the younger guys. So that's where I am now.

Julie Cohn (00:05:50):

So, if you were to try to characterize who you are within the world of power systems, would you describe yourself more as a theoretician? As somebody who focuses on applications? An academic versus a consultant? How would you characterize your role?

David Hill (00:06:13):

Well, I'd like to think all of those things. I have a student just finished a thesis on grid flexibility, and he proved theorems. But I just finished a major consulting job with the New South Wales government on energy preparedness, and I've just prepared a talk on the need for greater coordination in the energy transition. And I've done major consulting jobs in Europe, so at the risk of sounding like I'm evading your question, I think that that's the beauty of this subject. I embrace it as a complete subject where, like economics, you can prove—you can study mathematical questions, policy questions, economic questions, social questions. You need a big toolbox in this subject. But deep down, I acknowledge, I'm a systems and control person.

(00:07:21):

That's my base. But in this area, you need to be able to reach into—like recently—database methods, machine learning. How is AI going to influence running the future power system? So, I have my home base in systems and control science and engineering, but I do believe that ultimately people in this subject need to be able to engage with those broader aspects from policy—politicians interfere in this area. And then we have to talk to economists and social scientists. My good colleagues, one of my good colleagues, at Monash, she would not know much about power flow, but I need to talk to her about social license issues with farmers, and how we're going to plan a future grid. So, it's multifaceted. Sorry not to answer so precisely, but I'd like to think that we need to cover all these bases. Theory's important. Probably that's where I stick my neck out a bit more than others. I'm not afraid to give a student a theoretical question in this area at all, and generally we end up with the papers accepted somewhere.

Julie Cohn (00:09:01):

Well, as a theoretician who's made significant contributions to the industry, let's turn to some questions about what you look back on as the most important or significant challenges you tackled over the years related to power systems optimization and control.

David Hill (00:09:24):

Okay. Well, it's a good question. Generally, they've followed a similar pattern. First of all, instability. The first problem I ever got—in those days, it was a hot topic to come up with direct methods for transient—for stability assessment. The only problem was that the subject was ill—the foundations were not good in that the so-called energy functions that they were using were not actually valid theoretically. So, my colleague and I at Berkeley, we solved the problem by revising the model that's used. It's still a very simple model, but we revised the model and then the problem was easily solved. And then years later, I was in Sweden after a major voltage collapse. And the problem at hand was how to explain such a voltage collapse. There were some load-flow sort of solutions, but it was obviously a dynamic problem.

(00:10:39):

So once again, the answer was to find a simple model that captured the behavior, and then the theory just fell out. It was easy. Well, at least the first round of theory. You can always go deeper and harder. But the essential—I feel I've been lucky in that I've looked to get the right model, and then I can do the easy bit with the theory, and then PhD students can kind of pick up on harder aspects. And then later, years later, in Australia, we had a program to look at future grids, and there's no linear solution to the future grid. We've got rooftop PV in Australia. Enough to run the whole grid at certain times of the day. We've got new batteries, we've got a whole lot of new technologies, so there's no linear path forward.

(00:11:39):

So, then it becomes a scenario-based analysis. Once again, the model that you could put forward to analyze that, in the first instance, would be way too complicated. So, the emphasis, once again, was to find those, to keep it simple with this idea, that you keep it simple enough so that you, sorry, the background noise here, to keep it simple enough that you can make sensible analysis and then build on the complexity as needed. So, I followed that pattern. People say I'm a theoretician, and that's true. But when you're in an applied area, the model is everything. And I see so many bad papers where people stick to an existing model to solve a new problem. And I just think the first step is always to rethink the model. Like, over the years, I've had many people in optimization, in other areas, say, "David, give me a model. I've got a tool to solve."

(00:12:49):

And my answer normally is, "Look, I'm sorry, unless you're willing to rethink the model with me, maybe that's not the best approach." And I've had a couple of spectacular examples. One of them is Pascal Van Hentenryck, who—I forget where he is now, maybe in Georgia Tech—he is a constraint optimizer. And he took it a step further. Not only did he make his own model, he started doing load flow approximations as a research topic. But I thought that was terrific. He was willing to look at the models that suit his techniques, which was a highly scaled optimization. So yes, theory is important, but only when it's done on a model that you can then build on. And at some point, you have to give up on the theory and start becoming computational. And you can sometimes have both, side by side. In the voltage stability area, we had simpler models to develop the proximity indices, but then we had the more complicated models to do the simulations and so on to check details. So that, I think, summarizes my point there.

Julie Cohn (00:14:20):

Thank you. I see that Sairaj would like to ask a question.

Sairaj Dhople (00:14:26):

Yes. David, I believe you're referencing your early '80s work with Art Bergen on structure-preserving models, when you spoke at the very beginning here. For our audience, can you say a little bit more about that and where the inspiration for that came from, what it actually did, and what it achieved?

David Hill (00:14:44):

Well, actually, like I said, I think it wasn't that hard. I was someone who came from a PhD, proving theorems on stability and instability with functional analysis and the Lyapunov theory and so on. But I remember Art was at Berkeley, and I had just shifted over to the systems and engineering power program. It was—I think Felix Wu and Pravin Varaiya were the leaders of the Berkeley section of that program—as I said—led from DOE by Lester Fink. And then, there was this problem. As soon as I looked at the problem, I could see the so-called Liapunov function was not well posed. It was these—the classical power system model had transfer conductances, and there was only a rigorous Lyapunov function for I think the two-bus case, which was a bit limiting. But still people were going ahead using them.

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So, I thought, okay, here's a problem to solve. I didn't realize how hard it was, and in fact, it's still pretty much unsolved using the classical model. But then, it was just luck. Art, his book, *Power Systems Analysis*, these days, with the version also with Vijay Vittal. And his book was in draft form. And I was still learning about power systems. And he asked me to read it and make comments, just like he'd asked many people. And I found a few mistakes which made it worthwhile doing it. I thought it was a great book, and it's still one of my favorite, if not my favorite, textbook. But in that book, there was a very simple picture of a power system's load.

([00:16:51](#)):

Now, I forget the context, but it was not the usual impedance. Like in the standard classical model, all loads are modeled as impedances, which in hindsight's ridiculous. It's so old, such an old idea. But here was a model and it made me think. It was a—I can't remember quite the detail, but it looked like a dynamic model, but it was, but had a fixed power associated, rather, it was a fixed power model rather than a fixed impedance-type model. Anyway, in parallel with that, Art and I are starting to discuss this problem, and I just said to Art, "Look, it's this network reduction that's killing us. I mean, every time the network's loss-less, but every time you do this network reduction, you get these transfer conductances." So, Art has made a really, very simple but powerful comment along the lines of, okay, we'll find a way not to do that network reduction.

([00:17:55](#)):

And then we both knew about this constant power idea. The thing is, if you did pure constant power, you got a differential algebraic system. But in his model, there was a frequency-dependent term. So anyway, it was Art's idea not to do the network reduction. And it was in his book, or his notes, what kind of model. So, we threw it all together and we worked through the details, quite simple, and we got a rigorous Lyapunov function. Now, the reviewers almost killed the paper, because it was against the conventions. All the existing—we were minor people in the subject. But the leading people didn't like it because it was saying it was going to add to dimensionality, it was going to do this and this all along. But anyway, the paper got accepted. Now it's got, I don't know, like 7—or 800 citations, I think.

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But the beauty was, when you look at power systems these days, with renewable power and batteries and whatever, it's actually a very good, simplified model because it gives respect to the load buses as entities themselves. And in fact, there was a paper that came out some years later, Grijalva, I think, is the author, which showed that our model is actually a very good, simplified model for including renewable power buses. Because the first order load model can also be interpreted as a first order generator model, i.e. with no inertia. So, we kind of lucked out in that, a simple trick to make a rigorous Lyapunov function actually produced a model, which I think is way more useful than the classical model. So, does that answer your question there?

Julie Cohn (00:20:08):

Yes. And, oh, go ahead, Sairaj.

Sairaj Dhople (00:20:11):

Sorry. And if I may just follow up with that, David, it seems like, you pursued some of these modeling advances to get the math to work out, right? Like, were there practical sort of ideas or practical influences that also played into some of these early technical developments? And if so, where did those influences come from?

David Hill (00:20:38):

Well, yes. I think it's a good question. I think of research like a mountain stream coming down to the ocean, okay? So, without the upstream water, you don't get the flow into the ocean. If you think of the ocean as the practical world with all the outcomes, that can come from good solutions, you need that upstream activity. So, right then, in systems engineering for power, that was all motivated by making the US electricity grid more efficient. And there was an urgency to that. Reserve margins, like, I think the Russian power grid survived on reserve margins of a few percent when, with a lot of science. Whereas in the US the reserve margins were diminishing and were going down, but the science wasn't there.

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So that was, you can say that's a quite practical aim to make the whole US grid more efficient. And then come to transient stability. In those days, the computation was such that it was a serious endeavor to look for these direct methods in order to analyze all the contingencies on the grid. Using simulation had its limitations. It couldn't be done fast enough. So, there was a—very much a practical aim at the highest level, and at the next level, to get solutions that could be used in practice. The whole aim was to use these direct methods in control centers to do rapid contingency analysis. So, then I come along as a theoretician, and I think, well, this method's not well grounded, so I want to make it well grounded. And my immediate concern is not, will a million people read my theorem, but I just felt that, if the method had a stronger foundation, it will ultimately be more useful.

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So, it's all in that stream. I think what I don't like is what I grew to see, like in the control community. I feel they went off on a tangent too much there. You get theorems producing theorems, producing theorems in a loop. And that gets too isolated from practical applications. But what I liked in the power area was that you could see, and when we came to the voltage stability work, there was a definite practical need there. Systems were collapsing, and people didn't understand why, and they didn't know how to prevent it. So that's what I like about this subject is that you can do everything from theory. Although, okay, there are naysayers who say, Theory—it didn't help me solve my problem. But I think if you see it in a stream sense of upstream and downstream and practical applications, and you've got a place in that stream, I think you're useful. So yeah, that's my view on that.

Julie Cohn (00:24:24):

Thank you.

David Hill (00:24:25):

I mean, I could refer to Julie's famous father, right? If all those theoreticians hadn't invented classical control, maybe Nathan would've had less tools to solve the frequency control problem, so there you go.

Julie Cohn (00:24:48):

A good historical link there —and personal. So, when you were making your theoretical models available, what was the method by which you shared this information with others? Was it through this initiative that Lester Fink organized, or were there other pathways? And how did that move beyond the United States?

David Hill (00:25:17):

Okay, if I refer to the stability problems that I've already mentioned—in the transient stability case, that was my formative exercise in power systems. And it was a natural one because of my systems theory background. But actually, I didn't stick with it. I gave a couple of students projects and ultimately, I guess I have an inclination to: what's the big new issue? So that one passed to some extent, and you could argue that computation caught up. Now you wouldn't do research really on direct methods, because the computational capability, the AI capability, the database methods are probably a better way to go. But it was very much in the US. When I came back to Australia, that was not such a fruitful line of research for me.

(00:26:26):

Maybe I had a student, but I was looking for new things. And then I went on study leave to Sweden where there was a famous control engineering school, but very much with an outlook to the Swedish industry. And they had had, just in 1983, a huge voltage collapse, which blacked out, if I remember rightly, half the country. And so here I kind of completely forgot that I was a theoretician. I started talking to engineers about what happened. And as I already mentioned, we came up with this simple model, but the aim there was to first of all understand, and secondly, to prevent further system collapses. So, these collapses had happened in the US. They happened in France; they happened in South America.

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So, they were a serious issue, to prevent them. Basically, they were related to relocating major power plants further away from their major loads. People didn't want power plants in their backyard anymore. So, the transmission lines got bigger and longer, and impedance bigger, and then you could argue that's sort of what led to voltage collapses. So, it was very much motivated by me being in a control engineering department, but one with a fantastic tradition for addressing new, practical issues. Karl Åström is, I think almost anyone who knows anything about control knows who Karl Johan or Karl in Swedish, Karl Johan Åström, or Karl Åström in English is, and so just the culture there was: here's a big problem. How do we, how do we solve it? And my position in Sweden was funded by the industry. So, I felt that I should deliver something.

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So, I got talking to the engineers, and we came up with a whole program of work. And ultimately that got implemented. The students who came—the most valuable thing that comes from these programs is the educated students. I always think. Okay, I write a few papers. But these students that we educated through that program in Sweden, they went and were employed by Vattenfall and Sydkraft. And they were the ones who built the protection system that then led to their capability against future voltage collapses. So that was a turning point for me in a way. I felt after that project that I was a more serious power systems researcher.

Julie Cohn (00:29:40):

Do you recall what year that voltage collapse took place in Sweden?

David Hill (00:29:45):

'83, I think. And there's a famous picture of it in—over a period of—the frequency survived. So, AGC was working. But then there was a ripple of voltage, and then, just collapse. Four hundred kVs just completely collapsed. It's so dramatic. People, I think in the early days, people didn't believe that such a thing could happen. And it was clearly dynamic. It wasn't just a load flow solution problem. It had a dynamics to it, which is what intrigued me. I'm thinking, well, this needs a model. And it was obviously related to load recovery. And the engineers in Vattenfall, they were not theorists, right? They had a really good physical understanding that it related to load recovery, but they had this really complicated way of trying to capture it. And I just went back to my office, in about 10 minutes, wrote down the differential equation that I thought would fix it, and then—but that could have just died.

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But the culture at the time, the mood in Sweden was that this was such an important problem, that the engineers in Sydkraft, Southern Sweden Southern Power—who now went off and built a big consulting company. And in those days, those people were in Sydkraft and doing PhDs and so on. The boss of the company, they asked him, could we do system tests where we drop taps on big transformers? Now, there was no way that could happen in Australia. But this guy said, "Yes, okay, do it." So, they dropped taps on transformers and did the system tests that verified our model. So that got Daniel Karlsson his PhD. Now he is rich and famous in other ways. But that was quite, I think probably one of the more exhilarating periods of my career in that it involved coming up with a differential equation model, which kind of used my systems thinking. But then we had industry champions, Sture Lindahl, and then whoever his boss was who supported it. In another context, it could have just died in an IEEE paper.

Julie Cohn (00:32:19):

For those who might not be familiar with the terminology, can you explain what the drop on the transformers meant? What actually was happening?

David Hill (00:32:28):

Oh, well, voltage control—transformers take one voltage to another voltage, and you can think of that as a fixed ratio going from like 22 kV off a generator to 33 kV up to 66, 130 plus all the way up to 400, 500 in Australia. But you can also have this ratio variable, depending on the position of the secondary winding on particular taps. And these are normally fixed steps on a transformer. But if you suddenly change that tap setting, you set off a transient. It's a disruption in the system that can set off a transient. And we were developing a dynamic model, so we needed a transient to verify it. We needed to look at the response on the system and then look at the response that we got from our model, and see that they matched, in order to verify the model. That was a process of experimentally verifying a theoretical model.

Julie Cohn (00:33:41):

Was there any risk of causing a significant disruption to power service when you did that?

David Hill (00:33:48):

Well, that’s why we would never be able to do it in Australia. But I guess the managers at the time saw—well, that only a few years before, they'd seen their half of Sweden black out. So, they were in the mood to help researchers who were trying to solve—prevent this from happening again. So, I don't, personally, I don't think there was any risk of a major disruption, and certainly nothing more than you would get on a daily basis with things going wrong in switch yards. And so there was no risk of anything cascading. Maybe a small change of voltage that might affect a piece of equipment momentarily, but nothing serious. I'm pretty sure they worked that out.

Julie Cohn (00:34:46):

And did they schedule it during a low load time, or was there a concern about when it would take place?

David Hill (00:34:56):

To be honest, I forget those details. Daniel managed all that—the student—because he was an employee of the company. So, I'm sure they had a risk assessment strategy around all that. In my mind, what we were doing was not too dramatic, it's just that this is a very cautious industry. As I was just talking with some people about half an hour ago, I think the culture in this industry is more cautious than you would get in other industries, simply because electricity's dangerous, right? From telling our children not to poke things in power points at home to when you see your local distribution company replacing a power pole on your street with about 20 people standing around and the electricity turned off for a kilometer in all directions. It's a very cautious industry. So, I'm usually very confident that if I'm handing something like that over to people in the industry, it'll be more cautious than is necessary, not less.

Julie Cohn (00:36:12):

So, one more question related to the Swedish event, and then I'd like to ask you something a little more broadly related to that. Let me ask the broader question. So, in this instance, there was a tight working communication between academics, the industry, presumably local government, if there was concern about any eventualities with the test. But did you witness that in other parts of the world, or was that an extraordinary set of relationships between academia, industry, and others in Sweden?

David Hill (00:36:57):

Well, that is such a good question. And I'd like to spend a couple of minutes on it. First of all, it's the most exciting interaction I've had, and I'll illustrate it. Sture Lindahl, who's just retired from Gothia Power—these guys who were in Sydkraft, they, with all the changes, it's such a big story—I don't know where to start. These were the days of in-house expertise inside the utilities. We had a similar version here in Australia, like the electricity commissions had people writing papers on their problems and working with industry very closely. So, this was the tail end of that era in Sweden, where Sture Lindahl had a master's degree from Karl Åström's department in Control, and he was employing people with PhDs. And so, when I came along, I was not a threat to them at all.

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In fact, I remember going into a seminar where I was going to talk about our research on voltage stability. And Sture said to me, he says, "David, I want you to use the word bifurcation," because he'd already sensed that I was softening my language around the theory. And he said, "You have to mention the word bifurcation. These people need to understand that this is important." This was an industry leader. I mean, I would fall off my chair if I met an industry person say that these days. So, he was a guy who was a really good protection engineer. He knew his stuff, practically, but he also knew the value of science. So, for me, I would've obviously had limitations in those days in terms of my practical knowledge. But he embraced what I could bring to the project, and it was tremendously fruitful in many ways—not only the educated PhDs, but in terms of them coming up with practical solutions.

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So yes, for me, definitely the best. But the bigger issue here is, there are versions of that in other parts of the world. In Australia, like I mentioned, we had state-based electricity commissions that were typically connected to one university where there was an ongoing relationship, and that all got broken down with the restructuring, deregulation, whatever you want to call it. In the US—of course, Daniel knows better than me—but there were lots of centers—UIUC, Georgia Tech—that have survived through all these changes. But generally speaking, I think the situation we're in right now, where we're taking a hundred-year-old system, that that's been developed over decades of research, and we're restructuring it to be renewables-based, a whole new paradigm for delivering electricity—I honestly don't believe—we need that connection between research and innovative thinking and the energy transition more than ever.

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But I don't think it's strong enough. Certainly, in Australia it's a serious problem. In fact, the meeting that I just had here an hour ago with the Victorian government was about how to start getting that connection stronger. But the problem is, it's almost zero. It's almost like starting from scratch. So, they'll say, "Look, let's start with a project. The problem is they won't give us any money, and the people that are employed at Monash are already busy on other projects. So, we have this terrible situation where we need to impress them that universities and research is important to the energy transition, but there's actually not such a lot of funding for it. I don't know, maybe in the US it's a little bit better, but I see mixed messages in the US with, okay, the IRA, how does that affect research?

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And then you've got the possibility of another Trump era where it'll all get killed. So, some kind of consistent—we need to see the energy transition as a mega engineering project, like putting people on the moon or building a rail network across the country or road network or whatever. But in the meantime, it's in the hands of too many entities, all doing odd bits and pieces. So, I'm a little bit pessimistic, actually. One of our economists in Australia is talking about the serious possibility of energy dystopia, where we have a definite program for retiring coal-fired plants. It's an agenda. And there's a whole lot of fear out there that: can we manage this with such a fragmented mosaic of entities all involved? That we need better coordinated planning and so on.

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So, to summarize, it's a big, big topic I've just taken on there, that things get done when everyone's on the same page. And that humble exercise that I had in Sweden was a wonderful example of people being on the same page. We can't have this system collapse like that again. It's simply, that was the driving force. So, people shifted their attitudes to embracing something new, like a systems engineer getting involved in things. And we got good outcomes. But I'm afraid, I'd like to see more of that on the same page story, in terms of the energy transition. Otherwise, I fear that it's going to end up a bit of a mess.

Julie Cohn (00:43:46):

Thank you. Sairaj?

Sairaj Dhople (00:43:50):

Yeah, David, you bring up some very interesting points. I want to offer a little anecdote and then follow up with a question, if I might. During the course of our project, we came across a book that was authored by Nathan Cohn. It's a famous book, *Control of Generation and Power Flow on Interconnected Systems*. Really thin book, but basically says everything that has to be said about frequency control—I'm sure you've come across it.

David Hill (00:44:14):

Yeah, 1950, I think, right?

Sairaj Dhople (00:44:18):

Perhaps, I'm not aware of the date. But a date that I'm aware of was when this book was made out by Nathan to Professor Petar Kokotovic at the Allerton Conference in 1971. That's what the jacket of the book mentions, the copy that we had access to. And this is such a remarkable thing for us to come across, because here's a book written on control of power systems by someone in industry, made out to one of the foremost theoreticians of the time. Right? And it—

David Hill (00:44:47):

Well, Petar— Sorry to interrupt you, but I know Petar very well, and he's a passionate control and power person. He's one of the few control systems guys that I ever met—and like Karl Åström—who were deep down very interested in power systems problems. Might go back to his connections in Russia where the leading scientists were involved in the development of the power grid. Anyway, sorry to interrupt you. I know Petar.

Sairaj Dhople (00:45:24):

That's great to hear. And I'm sure Julie will pick up on a couple of things that you mentioned. But, just going back to that, I just wonder, was there a singular event or was it just a series of unfortunate events that resulted in these divides between industry and academia? Like, did we just get so good, with the grid working so well, that we made this technology so invisible? And as a result, a lot of the real challenges that are coming to the surface today were hidden for a long time. Like, what happened? Why is there such a big gap between industry and academia today?

David Hill (00:46:05):

Okay, well, the implication of your question is that you see that as an issue in the US as well, which I'm kind of vaguely familiar with. But in Australia, it's very clear. There was an existing power grid—and the Australian grid is a complicated one. It's arguably the longest grid; I think 5,000 kilometers from north to south. Stringy grid, all the way down the east coast of Australia. So of course, we had lots of oscillation problems and different problems over the years that got solved. But in the 1990s, it was basically all working. I mean, from an engineering point of view thanks to Nathan Cohn and all of those guys who worked out using eigenvalues to analyze dynamic stability and so on, the grid was in place.

(00:46:59):

It was just this neoliberal—about neoliberalism and economics, was that somehow, we can make all this more efficient. Now, I don't mean engineering efficient, I mean economically efficient, and I'll just assume the difference. But we can make all this more efficient. Now that flip is dramatic, because I think up until that point, electricity, clean air, secure streets, good roads, we kind of took all those as things that government provided and made sure. But they're all—with this neoliberalist approach that we make energy a competitive space. Electricity became a commodity that could be delivered in various levels of quality, and so on. So, we got electricity markets. And then, in the beginning with those markets in

Australia, economists and engineers were in the same room. The leading engineers were in the same room as the economists.

(00:48:19):

So, they could work out that, okay, well, we accept that we've got to have this change. It was called open access, deregulation. Of course, people sometimes call it re-regulation because there are still lots of regulators around, right? Initially probably not much changed, because you replace economic dispatch by a one-sided market, and it's an optimization algorithm. So, no big deal, right? So, I think initially—and then, prices did go down, at least in Australia, but they went down largely because of cost-cutting and sort of more business-type cost cutting, like research. They stopped funding research. It was one way to reduce costs. So, I think there's where in Australia, it kind of started to go wrong. Meanwhile they started spending more on consult—well, they cut research, and they took a more business-like mentality, and we got managing directors who were not engineers.

(00:49:36):

They were economists. In fact, one of the popular university courses in those days was teaching business-type managers the basics of electricity. So, a big paradigm shift came over an existing engineered system, that—there was nothing wrong with it. It's just that they wanted to turn it into a competitive commodity electricity. So, I think in Australia, at least, you can see that the costs did come down initially. But not really, I think, because of competition, but just because of cutting costs. And research went out the door with that. That was part of the cost cutting. Eventually, the costs have gone up. Price of electricity has gone up. And look, this is a complicated question, but one thing is they no longer fund research, but they pay an awful lot of money to consultants, which they need, ultimately you need more transmission lines and more equipment, and all that adds to the costs.

(00:50:53):

So that's the Australian story. It was the shift to a more business-based rather than a state-based. See, we had vertically integrated state-based systems here, and they still exist. In Hong Kong, that's still the model —vertically integrated system. Which has many advantages actually, when the demand side starts becoming more important. But yeah, in Australia, the disconnect with universities kind of came with the shift to deregulation. We had a funding body for research in power engineering, and that got disbanded. They basically took the view, well, if we need to know something, we'll hire a consultant.

Julie Cohn (00:51:44):

Interesting. I'll pause and see if Daniel, Rachel, or Rahul wanted to add anything further at this point or ask any additional questions at this point.

Daniel Molzahn (00:51:58):

Thanks, David. This has been really interesting so far. Maybe one kind of quick follow up on that is: so, you mentioned Hong Kong, sounds like it maybe preserved more of this research culture. Do you know how it was in the rest of the world at the time. In Europe or South America or other places, was the same—issues going on? Or was there not a whole lot of research in some of those places to begin with?

David Hill (00:52:33):

Oh, well, first of all, in Hong Kong, I wouldn't say, China Light and Power, Hong Kong Electric—they're entities in themselves. They don't give a lot of money to the universities there. And their university connections are international. Like Hong Kong Electric is closely connected to, what's it called, the Glasgow, the big power center in Glasgow, through personal connections, which is kind of a Chinese way. So, I wouldn't say the research culture in—as Felix Wu would tell you, weren't that strong in Hong Kong. But the vertical integration is what I referred to. You go to the control room in Hong Kong and distribution benches on one side and the transmission benches on another side. And that has advantages, of course, they can talk to each other in getting more coordinated control setups, for example. On the research university connection—

(00:53:40):

Okay, well, of course we see strong centers in Europe. The Danish Technical University has a very strong center in power systems research with many professors. Imperial College in London have just hired two new people, Mark O'Malley, Pierre Pinson, and Manchester. So, there are strong centers. I think in the UK there's a small part of your electricity tariff earmarked for research, which is something I'd love to see in Australia. And I'm told by Jovica Milanovich that that is what funds their research activities. So, I think in the UK it's stronger than Australia. In Europe, you've got these major centers, like where Göran Andersson was at ETH. Gabriela Hug has taken over there. I'm not a hundred percent sure of how funding's going for her, but I think in parts of the US that I've mentioned, and in parts of Europe, people like Imperial College never closed down power, to their credit.

(00:54:54):

Other universities, like my university now, Monash, they basically closed down power labs to build robotics labs. Now they're kind of regretting that. Whereas Imperial College stuck to power. Tim Green, I remember when he was just a young guy there and I'm thinking, wow, this is impressive. They've still got a few power people here. And now they've used that as a base to make it bigger and better. So, I think you have to look all over the world where people made decisions to preserve the power group in some form or another, and in other places they made the decision to close it. And that kind of helps describe where we are today. Now, of course, every university in Australia wants to hire power people, and that's why a gray-haired guy like me can still get, a job for a couple years. But the universities in Australia tried to get Ian back. They tried to get Ross Baldick back. Those horses had bolted, right, to the US. So, I think it's a mixed story. I think these days like the big universities in the US, MIT and Caltech and so on. You've got Steven Low at Caltech and MIT got Maria back, but they get themselves caught in a sense—

(00:56:34):

You need people who I think have a bit of a scientific outlook. Like you've been well educated with that, Daniel, but I do think the subject needs to be seen, coming back to my earlier point, as an important subject in its own right. With its fundamentals, with its practical applications. Instead of just being a practical—. It suffers by just being seen as like the practical end of other subjects. Yeah. Ask me to say it another way if you like, but I think, in parts of the world it's suffered because, like—Sydney University and Melbourne University in Australia are the oldest universities, and they were a little bit sniffy about power engineering. It's a practical area. We should be concerned with more fundamental things. So, okay. Sydney University had some people doing nuclear fusion as their contribution to the energy development. But it didn't go anywhere. They'd have been better off seeing power systems as a fundamental issue to deal with, if they really wanted to be in this area. Okay, Daniel, I'll leave it there and see if you want me to rephrase it in some way.

Daniel Molzahn (00:58:08):

No, that's great. That's really interesting. And I've seen some similar attitudes as what you're describing, so it's certainly not foreign in the US here as well.

David Hill (00:58:21):

Okay, good.

Julie Cohn (00:58:23):

It sounds like one could sum it up as follow the money, over the last five decades, or six decades. Rahul?

David Hill (00:58:31):

Yeah. Yeah.

Rahul Gupta (00:58:32):

Yeah. Hi, David; I had a related question. Basically, you mentioned vertically integrated systems, might be—I mean, they're more efficient in implementing policies because they have in one authority, DSOs. And DSOs—I recently saw that in Switzerland or in Germany, they are buying back the DSOs to impose such policies. So, do you think this is the way to go forward, for several systems in other parts of the world?

David Hill (00:59:07):

Okay, well, it's a really good question, Rahul. First of all, as a control engineer, control systems person, well, let's come to AGC. Nathan Cohn is getting mentioned here a lot. But AGC is not a centralized control structure. And it's more a distributed control structure. You've got the local primary frequency control, secondary, and even tertiary. So, it's a kind of layered approach to frequency control, which uses local control and uses a higher level of system-level control. And to me, that's a good paradigm for kind of implementing almost any decision situation. And in certain situations, you don't need the central component. You can just deal with agents talking to each other. So, this is my background to answering your question. So, I'm not necessarily saying we need to go back to vertical integration, with some kind of centralized control. But what needs to happen is that I always say the right people need to talk to the right people at the right time.

(01:00:27):

So, with ISOs and DSOs, I think all that can work with the right level of coordination. You can have, you could even have local peer-to-peer markets working with a national market. But there needs to be proper structure like there is in frequency control. Now, if I come to the Australian situation, after all those reforms, the idea was to take power away from the states, and to make a national market. Now there's questions about whether that national market makes sense as a complete answer, because distribution companies now, they have their own generation, lots of rooftop. They can even have small-scale wind farms, solar farms, and they can have community batteries. So, they've got the resources to make a—so we can see households, microgrids, distribution entities all the way to the national group. So, we need to rethink how all that operates.

(01:01:38):

And these distribution entities are looking to have more, they're pushing back a bit. They want more, say. They don't want to be just bossed around by the national entity. So, I hope I'm not wandering too far from your question, but we need to get that architecture in place where we respect all the energy coming off rooftops, which can go into a more local entity and can look after a lot of things locally. And then, what else do we need on top of that? At the moment, we've got a bit of a tug of war going on, where we're going gung-ho with what we call renewable energy zones and big new transmission and so on. But we've also got all this energy coming off rooftops. So much energy coming off rooftops that at some points in the day, we don't need energy from the—really, in principle, we don't need energy from a big grid.

(01:02:41):

So, I see an issue in working out DSOs, ISOs, distribution company. We need to reset how all that works together. I don't have an answer, but I believe from a fundamentals point of view, like I said: if you get the right entities, I believe in having as much of your problem solved locally. Just like in Nathan, in that frequency control error, a lot of the frequency control problem was solved locally. There was just this error that needed to be fixed. And then you fix that with a centralized problem. We need a version of that across the whole grid now, I think, where we solve as much as we can locally, and then see the big grid as fixing the gaps. That's from a control engineering point of view. And then the DSOs, ISOs, RTOs need the managers that implement that paradigm or that new structure. Is that okay?

Julie Cohn (01:03:59):

Thank you. I'm going to ask—

Rahul Gupta (01:04:01):

Yeah. Thank you.

Julie Cohn (01:04:02):

Go ahead. Yes. Did you want to follow up Rahul?

Rahul Gupta (01:04:06):

No, it's very good answer. Thank you.

Julie Cohn (01:04:10):

And at the risk of painting myself non-technical, if AGC is the algorithm we use today to maintain stability on, at least in the United States, we call it the bulk power supply, system—I assume you have something similar there—will it still be a relevant algorithm in this future paradigm you are somewhat imagining?

David Hill (01:04:35):

Well, actually I simplified a little bit. In Australia, Nathan Cohn frequency control is not used. But what happened was: instead of AGC, we've got, like, ten frequency control markets; they're all trying to do what AGC did. Can you believe it? The whole of the mainland grid is now one frequency control area. So, whereas previously it was state by state, which for me made much more sense. So, the pure AGC, that we've referred to as a model has been changed, to be implemented in terms of markets and—oh, it's complicated. When the restructuring happened, the initial inclination was to replace all those control engineering structures by competitive markets. Everything had to be competitive, but then they ran into trouble, so then they turned back on aspects of AGC.

(01:05:57):

So, I think at the moment, I would guess we've got a mishmash of some AGC aspect and new markets. Okay. And these new markets deal with frequency control in different time zones and also with contingencies. So already, not because of sensible engineering, I would say, just because of the business model that overtook the system, we don't have pure frequency control as Nathan Cohn invented. But I would argue that it's still trying to do the same thing, in another way. If we didn't have AGC at the outset, then we wouldn't be able to do what we're doing today. It's still kind of the benchmark.

(01:06:52):

It's a kind of complicated issue, and it's a bit—I have engineers in Australia, older engineers who rail against this. Why did we turn AGC—Why did—it's a control problem. Why are we turning it into a whole pile of markets? But yeah, that's just how things turned out. So, what happens in the future depends on, do these markets come unstuck? They're now talking about new markets for inertia, for system strength. And I'm freaking out over that because, how will these markets interact? When it's a control problem?

You put it all on the same page and you come up with an optimal answer. When it's markets, you make a market, you see what happens. If it doesn't work properly, you make another market to try and fix the previous market. And it just goes on. And all these markets can end up interacting with each other with unintended consequences. So, this is the state of play, unfortunately, for the future.

Julie Cohn (01:08:05):

Interesting. But so far, no major power failures?

David Hill (01:08:11):

No, that's true. Well, in Australia, we've had a major collapse in 2016, but not much before that. And of course, they blamed renew-. What happened was, we had a once-in-50-year storm that blew—it was actually so strong, it blew over transmission towers at a time when an interconnector with another state was in a reduced state, reduced capacity, and we got a blackout. And then the naysayers blamed renewable power. They said, It's all about the wind turbine. So, this is where all the media intrusion just muddies the waters. And of course, at the end of the day, it did come down. There was a problem with the wind turbines, but it wasn't the obvious one. It was just simply that their control settings at the moment are somewhat secret.

(01:09:16):

They only hand over so much information to the market operator. And this is a problem we need to solve. In the old days, all the data was available. But now the vendors for equipment, like wind turbines and so on, they want to keep a lot of their control settings secret. And I argue that that could have serious unintended consequences as played out in that situation. Now their argument is, well, it was a once-in-every-fifty-year storm, why should we worry about that? But these things happen. In fact, the joke in Australia is that we seem to be getting once-in-fifty-year events almost every year lately, with floods and cyclones and climate. And this is an interesting part of our whole story here, that we're trying to invent a new system during the consequences of the old system mucking up our climate.

(01:10:25):

If you see what I'm saying. We have to design—so a lot of our past paradigms for planning, for instance, were related to consistent patterns of weather. Now, we don't have, I don't think anyway in Australia, to go back five years, we've had major bush fires, three years of floods. Then this year we're supposed to be an El Nino year where we're going to get more bush fires, and meanwhile, it's raining every day. So, we're designing a new system, which is extremely weather based, during a time when the weather's changing. And that makes our job much more difficult. So, we're more likely to get extreme weather events now. And most of, at least in Australia, our planning paradigms don't allow for that. So-called, they don't allow for resilience, they allow for reliability, which is a big issue.

Julie Cohn (01:11:31):

Speaking of resilience and reliability, would you venture to distinguish between stability, reliability, and resilience on power systems?

David Hill (01:11:42):

Oh, such a good question. Okay. I think stability is the most misused word in the public discussion around power system. For me, stability is about dynamics. The system gets a disturbance, and then the stability is about whether it returns to [an] acceptable state, doesn't necessarily need to be where it was, but it needs to be an acceptable state. So, for me, if I talk about the stability of an airplane, I'm not talking about whether it was full of customers, or how old the pilot is, or whatever. I'm simply talking about the fact that if a wind gust hits the plane, that it wobbles a bit and it returns to an acceptable operating state. It may even be at a lower height than where it was before. So that's stability. But often in the public discussion, when people say the word stability, they just mean the lights are on.

(01:12:44):

That there's power balancing. Okay? So, the concepts for me are power balancing, which means energy balance, power, balance, and ramping balance. Ramping balance means that if the load goes up quickly, the generation can go up quickly and similar. So that's balancing. Stability means when the system is disturbed, it comes back to an acceptable operating point. Reliability is a long-term, probabilistic concept where, with all the things that happen, lightning strikes, failures, a piece of equipment fails. All those quite high-probability events, but nothing that will collapse the system. The way power systems are traditionally designed, odd equipment failures shouldn't affect the balancing. So, reliability is a long-term, probabilistic concept of high probability, low impact events. How many hours in the year aren't the lights on? Unserved energy. Reliability is about unserved energy. Resilience to me, and I believe this is—the IEEEs recently had task forces on these things.

(01:14:12):

So, I was part of those. So, the concept there, now in biology, resilience is an important idea about your ability to survive, or a species to survive. So, despite changes in weather and so on, it adapts. The species adapts to all the changes around it. It doesn't mean after a major event, like, we could argue that the dinosaurs weren't resilient, right? Something went wrong and they couldn't adapt. It doesn't mean you stay where you are, it means you adapt to the circumstance. So, we can think of ourselves as resilient. We get older, we have different circumstances around us, but we survive. Coming to power grids that tends to get interpreted as the ability to survive the low probability, high impact events. So, in the past, like the big collapse in Sweden, that was a low probability event, which collapsed the grid, but there was no resilience there.

(01:15:32):

The grid couldn't recover. Half the grid was dead, and it needed to be rebuilt. So, resilience, if you said, "The grid was resilient," you would say there were mechanisms built in—first of all, that may have actually prevented the collapse. But certainly, mechanisms that if the collapse happened and we had to restore, that we're better off afterwards. There were learnings. Yeah. Okay. Maybe gone too far there. I think resilience in the grid generally means the ability to absorb bigger events and in particular to learn and adapt to them. Whereas the reliability model is: we can survive all these small events, and we'll end up losing electricity for a few hours. But the problem with that is, if you have a big blackout and the whole of Melbourne is black for a few hours, you can still satisfy your reliability criteria, because averaged out across the whole grid, it can still look okay, but that doesn't help the people in Melbourne. They want to know that this can't happen again. So that's where resilience kicks in, that the system can prevent these big, low probability events, have a way to prevent them, and adapt to the circumstances which caused them. Ah, okay. That's my tutorial. Finished.

Julie Cohn (01:17:11):

Excellent tutorial. Thank you. We don't want to keep you a whole lot longer this morning in Australia and evening where we are. So, I'm going to see if Daniel, Sairaj, or the others have any additional questions they want to ask. Then I have one more, and Sairaj has his closing question.

Sairaj Dhople (01:17:33):

David, I do have a question, if I may, Julie. You've mentioned several people that have definitely had longstanding contributions to the area. If you had to pick, maybe, a couple of personal heroes, who would they be and why?

David Hill (01:17:56):

Oh, that's a hard one because there's the objective story, the heroes—who's made the biggest impact on the subject? But then who's had the biggest impact on my development? In terms of big—I don't think I need to go back, in history to Edison and Tesla and Heaviside and then Nathan Cohn and—those people speak for themselves. But in my life, I mentioned Felix Wu who employed me as a postdoc, who had faith in me as a postdoc who had no previous experience in power systems, to employ me on the big systems engineering for power project at Berkeley. Karl Åström, who had the faith to give me a guest professorship in a famous control department in Sweden, when really my only prior experience in power systems was theoretical.

(01:19:11):

And those people that I mentioned there like Sture Lindahl. And then, in Australia, it's been mixed, but I've had people in industry who've supported me over the years. Ashok Manglik, Cole Parker, and so on. So, it's a mix. I'm aware of the heroes. I mean, you can go back to even Russia where, Gorev, there's a famous guy there, I think he's like their version of Park in the US. But he and Stalin—I've heard stories that he and Stalin didn't get on so well. So, he used to sometimes, Gorev, or some figure like him, were major scientists, but they'd lock him up and then they'd have to let him out to get on with his research. So, there's all these stories about legendary figures that have made major contributions, which is what kind of upsets me a bit in the current context, because we see it all in terms of economics and policy. But in actual fact, grids are hard. I mean, figuring out how to analyze and control a grid is hard science. So, I'm aware of those older figures, but I'm also highly aware of the people that made my journey possible. I'll leave it there. Thank you.

Daniel Molzahn (01:20:47):

And, Julie, if I have time to ask a question as well. So, David, the question I had was, last year, just over a year ago, you had your Bode lecture, which I thought was just a really brilliant exposition of the role of controls and power and I really enjoyed it. And so, I had a two-part question for you following up on that. So, in many ways that was sort of a call to arms, right? To the controls community?

David Hill (01:21:13):

Yes. Oh, I mean, good on you for realizing that's—I had a choice, I could have done stability theory or something else, and I said, "I feel—" Well, I don't want to preempt the second part of your question, so go ahead.

Daniel Molzahn (01:21:27):

So, the first part was, what have you seen come out of that? Has the community responded? And, how so? You are shaking your head "no," so it sounds like not. So that was the first part. The second part of my question was, are there other communities that you would see as needing that same call to arms, or similar style call to arms to come look at these problems in this space? What would be maybe a couple other communities that you think would be most valuable to give a similar talk to?

David Hill (01:22:02):

Okay. Well, yeah, good question. I really agonized a little bit over what to talk about, because the year before Pramod had given a talk on control for climate change. How control can—and I'm thinking, as much as I respect Pramod Khargonekar, I thought, no, it needs to be more concrete than this. We need to go back to the Nathan Cohns and people that really thought seriously about how can—the control community, I'm a bit disappointed with. I mean, not people like Ian Hiskens or Steven Low or those. You obviously realize I highly respect them, but the community as a whole tends to be a bit tokenism towards the power area. And so, I chose that lecture to say, "Hey, look, this is my journey in that subject, and there's been hard problems."

(01:23:07):

And, not only that, there's a lot of new problems. But of course, I got some kind comments back. Peter Caines was kind, and yeah, a few people said nice things about the talk. But I don't really feel as a call to ask, it was anything too successful. Okay, so in terms of new areas, well, the obvious one is AI, right? And the role of—we could sit here for another hour if we want to talk about generative AI and large language models, and so on. But they're coming, right? So, I think we're going to have to deal with them one way or another. My fear with those is that they're just not accountable. So, if we're going to develop large language models that are useful for the power area, then people like you and I need to be involved.

(01:24:09):

We can't just hoover up all the things that have ever been said about power systems, and regard that as a solid base for what to do next, which is kind of the para-—that's the—I'll probably get shot for this one day, but I sort of think of ChatGPT as like probabilistic plagiarism. It's not plagiarism, but it picks little pieces of everything that's ever been done and then merges it into a new story. And so, I'm a bit skeptical about that. But I do think there's no way we can avoid—we've got to embrace that as a new paradigm for doing things. And I think there are areas where it can be extremely useful, like maybe predicting weather or whatever, but—so that's certainly an area that we could get interested in our versions of the problems that need to be solved. I mean, optimization has been there for a while already. At Monash here, there's a whole department of optimizers and one of them set up a company already for the energy industry. So, I feel optimization can be improved. But it's already engaged. I think the control community should reconnect as I tried to get some motivation for. But—and we can improve areas like optimization, but maybe AI's the big one.

Daniel Molzahn (01:25:58):

Got it. That's really interesting. I'm sorry to hear that you haven't had a resounding army come to your call from the Bode lecture.

David Hill (01:26:06):

Well, I'm chipping away. At the moment I'm in Australia. I'm giving a talk wherever I can. Just on the systems aspect. I've backed off on control and I've said, "We need better systems engineering," I call it systems, energy transition systems engineering is my current my current catch cry, if you like. Yeah. And control fits in the picture, but we've got to get the idea that this is a big systems project first and yeah, well—I was reading this morning about—. I'm afraid in the US you face an uncertain future in that sense, given the outcome of your presidential election. The IRA's been a big inspiration all around the world, but I don't imagine its future would be too strong under the alternative leadership.

Julie Cohn (01:27:11):

We have engaged you in conversation for nearly an hour and a half now, for which we are deeply grateful. I think based on the last few comments you made, I'm going to turn over the final question to Sairaj.

David Hill (01:27:28):

It's been a pleasure, by the way. I haven't even felt the passage of time, so—

Sairaj Dhople (01:27:35):

Excellent. I'm so glad to hear that, David. And likewise. Just a question that I've asked a majority of the interviewees. Any words of advice for a future generation of hopeful power engineers entering this field? What would you recommend that they do?

David Hill (01:27:59):

Oh well, I'd say, "Be optimistic despite those last comments; these are passing things." I've actually been telling young people, "Wow, you're in a fantastic stage of history for the development of our energy system. We don't quite know what the final state will be." We talk about all these milestones for emissions reductions and so on out to 2050, but seriously, there's quite a lot of uncertainty about how this is going to develop. But, for the people like you, that's good, because that means there's going to be problems to solve, jobs will be there. And I'd like to think jobs in universities too, and that there's signs of that happening. I see jobs advertised on Power Globe. They're not conventional jobs necessarily, but like Tesla is employing power systems engineers.

(01:29:06):

So, I think it's—be optimistic. But also, be flexible that the jobs are not necessarily traditional jobs. As in traditional power utilities, hiring a load forecasting engineer or something like that. Be flexible. Like I would if I had to make one positive comment about my own attitude was that I don't feel I was ever a hammer looking for a nail, as it's sometimes described. I've always thought that this is an area where you solve problems. Now it helps to have certain skills, like control theory or optimization or understanding of electricity markets. But whenever you come across a problem, you will not be able to apply a tool that you know. You're going to have to go through an exercise of modeling and maybe even learn about new tools. But take the problem solving, think of yourself as a problem solver in an exciting new era. And if you take that view, I think you'll succeed.

Sairaj Dhople (01:30:40):

Thanks, David.

Julie Cohn (01:30:42):

Thank you so much. We really appreciate your time and your insights and your wisdom. It's been really fun for all of us, I'm sure.

David Hill (01:30:51):

Oh, and for me, thank you for the opportunity.

[End of interview]